Annotated Bibliography for Kevin Zahnle

J. F. Kasting, K. Zahnle, & J. C. G. Walker (1982). "Photochemistry of methane in the Earth's early atmosphere." *Precambrian Res. 20*, 121–148.
Introduced concept of hydrocarbons other than methane as greenhouse gases on Arheaan Earth

K. Zahnle & J. C. G. Walker (1982). "Evolution of solar ultraviolet luminosity." *Rev. Geophys. Space Phys. 20*, 280–292.
First synthesis of the history of solar UV and EUV emissions; it has held up well.

J. C. G. Walker & K. Zahnle (1986). "Lunar nodal tide and distance to the Moon during the Precambrian." *Nature 320*, 600–602.
Clever, but the Ediacaran varves later turned out to be ordinary tides. It's still not clear what the periodic varves in a 2.5 Ga BIF are.

K. Zahnle (1986). "Photochemistry of methane and the formation of hydrocyanic acid (HCN) in the Earth's early atmosphere." *J. Geophys. Res. 91*, 2819–2834.
Showed that HCN can be photochemically generated from CH4 in CO2-rich atmospheres. Also showed that organic hazes form in atmospheres with more CH4 than CO2.

K. Zahnle & J. F. Kasting (1986). "Mass fractionation during transonic escape and implications for loss of water from Mars and Venus." *Icarus 68*, 462–480.
Confirmed that quasi-hydrostatic formulae describing the escape of heavy minor species in hydrodynamic fractionation hold for transonic escape. Showed that both hydrogen and oxygen can escape from Venus in energy-limited escape.

K. Zahnle & J. C. G. Walker (1987). "Climatic oscillations during the Precambrian era." *Climatic Change 10*, 269–284.
Showed that the solar semidiurnal thermal tide was resonantly forced in Earth's atmosphere when the day was 21 hours long. The resonance would have dominated tropical weather during the NeoProterozoic ca 700 Ma.

K. Zahnle & J. C. G. Walker (1987). "A constant daylength during the Precambrian?" *Precambrian Res. 37*, 95–105.
The Sun's pull on the semidiurnal thermal tide speeds up Earth's rotation by extracting angular momentum from Earth's orbit. Near resonance this torque would have been as large as the usual lunar torque that slows Earth's rotation.

K. Zahnle, J. Kasting, & J. Pollack (1988). "Evolution of a steam atmosphere during Earth's accretion." *Icarus 74*, 62–97.
Our attempt to show that Abe and Matsui were wrong led us to conclude that Matsui and Abe were correct: accretional heating was sufficient to maintain a steam atmosphere over a magma ocean in a runaway greenhouse state. Our model included outgassing, impact erosion, and a host of other cool details.

J. Kasting, K. Zahnle, J. Pinto, and A. Young (1989). "Sulfur, ultraviolet radiation, and the early evolution of life." *Origins of Life 19,* 95–108.
A sleeper. This paper invented reduced sulfur photochemistry for early Earth. We predicted that S8 – elemental sulfur – would make aerosols that would precipitate to the surface. This prediction was spectacularly confirmed in 2000 by the discovery of anomalously fractionated sulfur isotopes in Archean sediments that are now believed to record the history of oxygen on Earth.

N. Sleep, K. Zahnle, J. Kasting, and H. Morowitz (1989). "Annihilation of ecosystems by large asteroid impacts on the early Earth." *Nature 342,* 139–142.
This paper emphasized that, when the lunar late heavy bombardment is translated to Earth, the impacts preferentially annihilated near-surface, cool-living ecosystems, such that it is inevitable that - if life were present on Earth during the heavy bombardment – life on Earth today must have a hyperthermophilic root.

H. J. Melosh, N. Schneider, K. Zahnle, and D. Latham (1990). "Ignition of global wildfires at the Cretaceous/Tertiary boundary." *Nature 343,* 251–254.
Empirical evidence of a global soot layer at the K/T boundary suggests that the impact caused massive biomass burning. This paper explains how Jay thinks the K/T impact set the world on fire.

K. Zahnle, J. Kasting, and J. Pollack (1990). "Mass fractionation of noble gases in diffusion-limited hydrodynamic hydrogen escape." *Icarus 84,* 502–527.
Addresses escape of noble gases from atmospheres that contain an abundant heavy constituent (e.g. N2 or CO2) as well as hydrogen.

K. Zahnle, J. Pollack, and J. Kasting (1990). "Xenon fractionation in porous planetesimals." *Geochim. Cosmochim. Acta 54,* 2577–2586.
Here we developed Ozima's hypothesis that the mass fractionation of xenon isotopes (seen only in planetary atmospheres) took place by gravitational settling inside porous planetesimals.

K. Zahnle and D. Grinspoon (1990). "Comet dust as a source of amino acids at the Cretaceous/Tertiary boundary." *Nature 348,* 157–160.
Another too clever paper; it inspired a NY Times OpEd piece (illustrated with a comet in the traditional role of the stork!) and a fine essay in Nature by Chris Chyba on the history of Occam's Razor.

K. Zahnle (1990). "Atmospheric chemistry by large impacts." In *Global Catastrophes in Earth History*, eds. V. Sharpton and P. Ward, G.S.A. Special Paper 247, 271–288.
Although the referee enumerated 43 reasons not to publish this paper, it's actually not bad. It addresses impact shock chemistry over all scales, from meteors to giant impacts. It also contains a full description of how I think the K/T impact set the world on fire.

K. Zahnle, J. Pollack, D. Grinspoon, and L. Dones (1992). “Impact generated atmospheres over Titan, Ganymede, and Callisto.” *Icarus 95,* 1–23.
This study showed that impact erosion of atmospheres can be a strong discriminant between Titan and the Galilean satellites. The key is that impact velocities on Titan are lower than on Callisto and Ganymede, and hence Titan has a better chance of retaining an atmosphere.

K. Zahnle (1992). “Airburst origin of dark shadows on Venus.” *J. Geophys. Res. 97,* 10243–10255.
This paper discusses how asteroids and comets break up and explode when striking planetary atmospheres. The paper discusses the atmospheric explosions and effects on the surface from asteroids and comets that don’t reach the surface, and it compares the size-number statistics of the impact craters made by asteroids and comets that do get through the atmosphere to the observations made by Magellan.

K. Zahnle & L. Dones (1992). “Impact origin of Titan's atmosphere.” *Proc. Symposium on Titan,* (ESA SP-338).
This recycles an earlier paper for a conference volume.

K. Zahnle (1993). “Planetary Noble Gases.” In *Protostars and Planets III,* eds. G. Levy, J. Lunine, and M. S. Matthews, University of Arizona Press, 1305-1338.
This was a rushed, and not entirely successful, review of planetary noble gases.

H. B. Singh, D. Herlth, D. O'Hara, K. Zahnle, J. D. Bradshaw, S. T. Sandholm, R. Talbot, P. J. Crutzen, & M. Kanakidou (1992). “Relationship of PAN to active and total odd nitrogen at northern high latitudes: Influence of reservoir species on NOx and O3.” *J. Geophys. Res. 97,* 16523-16530.

K. Zahnle (1993). “Xenological constraints on the impact erosion of the early Martian atmosphere.” *J. Geophys. Res. 98,* 10899-10913.
This paper addresses the consequences of impact erosion of atmospheres for Mars. The main conclusion is that impact erosion predicts either a thick atmosphere or no atmosphere, hence a thin atmosphere such as Mars’s requires an additional process (e.g. trapping of atmospheric gases in the regolith for later release).

M. Ozima & K. Zahnle (1993). “Mantle degassing and atmospheric evolution: Noble gas view.” *Geochem. J. 27,* 185-200.
Among other things, this paper emphasizes the difference between atmospheric and mantle neon isotopes, which can be explained by escape of atmospheric neon.

C. Chyba, P. Thomas & K. Zahnle (1993). “The 1908 Tunguska explosion: atmospheric disruption of a stony asteroid.” *Nature 361,* 40-44.
This paper applied the model developed for aerodynamic disruption of asteroids striking the atmosphere of Venus to the famous Tunguska explosion on Earth.

H. B. Singh, D. Herlth, D. O'Hara, K. Zahnle, J. D. Bradshaw, S. T. Sandholm, R. Talbot, G. L. Gregory, G. W. Sachse, D. R. Blake, & S. C. Wofsy (1994).

"Reactive nitrogen in the northern high latitude atmosphere of eastern Canada." *J. Geophys. Res. 99,* 1821-1835.

K. Zahnle & M.-M. Mac Low (1994). "The collision of Jupiter and Comet Shoemaker-Levy 9." *Icarus 108,* 1-17.
This is a prediction paper for what the fragments of the Shoemaker-Levy 9 comet will do when they strike Jupiter in 1994.

M.-M. Mac Low & K. Zahnle (1994). "Explosion of Comet Shoemaker-Levy 9 on entry into the Jovian Atmosphere." *Astrophys. J. Lett. 434,* L33-L36.
This is another prediction paper for what the fragments of the Shoemaker-Levy 9 comet will do when they strike Jupiter in 1994.

O. B. Toon, K. Zahnle, R. Turco, & C. Covey (1995). "Environmental perturbations caused by asteroid impacts." In *Impact Hazards,* T. Gehrels and M. S. Matthews, eds., The University of Arizona Press, 791-826.
This is a compendium of bad things that comet and asteroid impacts can do to Earth. The emphasis is on the sources and consequences of optical depth, and what size of event causes darkness at noon or impact winter.

C. Griffith & K. Zahnle (1995). "Influx of cometary volatiles to planetary moons: The atmospheres of 1000 possible Titans." *J. Geophys. Res. 100,* 16907-16922.
This study addresses impact erosion and impact supply of atmospheres using a Monte Carlo model. The study shows how thin atmospheres can arise by chance.

K. Zahnle, M.-M. Mac Low, K. Lodders, & B. Fegley (1995). "Sulfur chemistry in the wake of Comet Shoemaker-Levy 9." *Geophys. Res. Lett. 22*, 1593-1596.
This study computed the evolving chemical composition in the impact plumes of Shoemaker-Levy 9. The presence of S2 implies high temperatures and very low pressures.

K. Zahnle & M.-M. Mac Low (1995). "A simple model for the light curve generated by a Shoemaker-Levy 9 impact." *J. Geophys. Res. 100,* 16885-16894.
This should have been a prediction paper for what the fragments of the Shoemaker-Levy 9 comet would do when they strike Jupiter in 1994, but instead its an explanation paper of what they did. It uses the same arguments I used in 1990 for how the K/T impact set fires on Earth.

K. Zahnle (1995). "Bangs or Whimpers." In *The Great Comet Crash,* J. Spencer and J. Mitton, eds., Cambridge University Press.
The concluding paragraph is a collage of song lyrics, song titles, a movie title, and other debris. A quote from this paragraph was used by George Will (attributed to "a NASA scientist").

K. Zahnle (1996). "Dynamics and Chemistry of SL9 Plumes." In *The Impact of SL9 with Jupiter, IAU Conference Proceedings,* K. Noll, H.A. Weaver, and P.D. Feldman, eds., Cambridge University Press, pp. 183-212.

This is a review of the SL9 impacts that emphasizes the chemistry of the plumes. The plume chemistry was generally strongly reduced, indicating that the comet was either water-poor or that water vapor failed to mix with reduced gases in the explosion.

W. B. McKinnon, K. Zahnle, B. Ivanov, & H.J. Melosh (1997). "Cratering on Venus: models and observations." In *Venus II,* S.W. Bougher, D.M. Hunten, and R.J. Phillips, Eds. University of Arizona Press, Tucson. pp. 969--1014.
A review chapter.

K. Zahnle & N. H. Sleep (1997). "Impacts and the early evolution of life." In *Comets and the Origin of Life,* P. Thomas, C. Chyba, & C. McKay, eds, Springer-Verlag, pp. 175-208.
This is a much expanded and improved revision of the 1989 Nature article.

O. B. Toon, K. Zahnle, R. Turco, C. Covey, & D. Morrison (1997). "Environmental perturbations caused by the impacts of asteroids and comets." *Rev. of Geophys. 35,* pp. 41-78.
This is an improved compendium of bad things that comet and asteroid impacts can do to Earth.

K. Zahnle (1997). "Leaving no stone unburned." *Nature 383,* 674-675.

K. Zahnle (1998). "Rocky Horror Picture Shows." *Nature 394*, p. 435.
Reviews of two movies: Deep Impact and Armegeddon.

K. Zahnle (1998). "Origins of Atmospheres." In *Origins.* C. E. Woodward, J. M. Shull, & H. Thronson, eds. Astron. Soc. Pacific Vol. 148. San Francisco. pp. 364-391.
An overview chapter that argues that the presence or absence of atmospheres in our Solar System is best understood as a competition between volatile sources and volatile sinks (i.e. escape to space).

K. Zahnle, L. Dones, & H. Levison (1998). "Cratering rates on the Galilean satellites." *Icarus* 136:202-222.
An update of Shoemaker and Wolfe's classic 1982 study, making use of modern understanding of the origin of Jupiter-family comets in the Kuiper Belt.

N. H. Sleep & K. Zahnle (1998). "Refugia from Asteroid Impacts on Early Mars and the Early Earth," *J. Geophys. Res. 103,* 28529-28544.
A comparison of how life might survive very big impacts on early Earth and early Mars. The paper presents the lead author's argument that life now on Earth first arose on Mars.

J. I. Moses, K. Rawlins, K. Zahnle, and L. Dones (1999). "External Sources of Water for Mercury's Putative Ice Deposits," *Icarus 137,* 197-221.
How water from comets striking Mercury can end up in Mercury's polar caps.

S. J. Kim, M. Ruiz, G. H. Rieke, M. J. Rieke, & K. Zahnle (1999). "High temperatures in returning ejecta from the R impact of comet SL9." *Icarus 138,* 164-172.
The temperature of CO emission in this SL9 event was observed to increase monotonically in time precisely as a simple ballistic model terminating in a reentry shock predicts.

H. F. Levison, M. J. Duncan, K. Zahnle, M. Holman, & L. Dones (2000). "Planetary Impact Rates from Ecliptic Comets." I*carus 143,* 415-420.
Updated impact rates of stray Kuiper Belt objects on planets.

D. G. Korycansky, K. J. Zahnle, & M.-M. Mac Low (2000). "High resolution calculations of asteroid impacts into the Venusian atmosphere." *Icarus, 146,* 387-403.
Detailed numerical modeling of big weak asteroids striking a thick planetary atmosphere.

De Pater, I., D. Dunn, P. Romani, K. Zahnle (2001). "Comparison of Galileo probe data with ground-based measurements." *Icarus 149,* 66-78.

A. D. Anbar, G. L. Arnold, S. J. Mojzsis, & K. J. Zahnle (2001). "Extraterrestrial Iridium, Sediment Accumulation and the Habitability of the Early Earth's Surface." *J. Geophys. Res. 106,* 3219-3236.
A rationalization for why we didn't see any exogenous Ir in putatively 3.86 Ga terrestrial metasediments.

N. H. Sleep & K. Zahnle (2001). "Carbon dioxide cycling and implications for climate on ancient Earth." *J. Geophys. Res. 106,* 1373-1399.
Seafloor weathering is suggested as an important sink on seawater CO2. Unlike subaerial continental weathering, seafloor weathering does not provide a smooth temperature feedback that allows for thermostatic regulation of surface temperatures. This makes the ancient Earth under the faint young Sun more prone to freeze over.

H. F. Levison, L. Dones, C. R. Chapman, S. A. Stern, M. J. Duncan, & K. Zahnle (2001). "Could the late lunar bombardment have been triggered by the formation of Uranus and Neptune?"*Icarus 151,* 286-306.
This has been superceded by the Nice model that ties the late lunar bombardment to the migration of the giant planets.

N. H. Sleep, K. Zahnle and P. S. Neuhoff (2001). "Initiation of clement surface conditions on the earliest Earth." *Proc. Nat. Acad. Sci. 98,* 3666-3672.
It is shown that there is no stable buffer that can maintain CO2 on early Earth at 3 bars needed to maintain a clement climate under the faint young Sun.

K. Zahnle, P. Schenk, S. Sobieszczyk, L. Dones, and H. Levison (2001). "Differential cratering of synchronously rotating satellites by ecliptic comets." *Icarus 153,* 111-129.

We compare the strong predicted asymmetry in impact cratering between leading and trailing hemispheres of synchronously-rotating satellites of the giant planets to the near-total absence of any evidence of this effect.

D. C. Catling, C.P. McKay, & K. Zahnle (2001). "Biogenic methane, hydrogen escape, and the irreversible oxidation of the early Earth." *Science 293*, 839-843.
It is suggested that the oxidation of Earth by hydrogen escape is the root cause of the rise of oxygen. The escaping hydrogen comes from methane, which served as an important greenhouse gas in the Archean.

K. Zahnle (2001). "The decline and fall of the martian empire" *Nature 412*, 209-213.
In which the 83 year old Alfred Russel Wallace has little trouble dispatching Percival Lowell.

De Pater, I., D. Dunn, P. Romani, K. Zahnle (2001). "Comparison of Galileo probe data with ground-based measurements." *Icarus 149*, 66-78.

D. G. Korycansky, K. J. Zahnle, & M.-M. Mac Low (2002). "High resolution calculations of asteroid impacts into the Venusian atmosphere II: 3D." *Icarus 158,* 1-23.
Detailed numerical modeling of big weak asteroids striking a thick planetary atmosphere.

K. Zahnle & N.H. Sleep (2002), "Carbon dioxide cycling through the mantle and implicatons for the climate of ancient Earth" In *The Early Earth: Physical, Chemical and Biological Development.* Geological Society, London, Spec. Pub. *199,* 231-257.
A revision of Sleep and Zahnle 2001 that considers much less vigorous sea-floor spreading rates.

D. Catling and K. Zahnle (2002). "Evolution of atmospheric oxygen." In *Encyclopedia of Atmospheric Sciences* (Ed. J. Holton, J. Curry, J. Pyle), Academic Press, New York.

T. L. Segura, O. B. Toon, A. Colaprete & K. Zahnle (2002). "Environmental effects of large impacts on Mars." *Science 298*, 1977-1980.
This study suggests that impacts are the chief cause of Martian hydrological activity, rather than an as yet unidentified greenhouse gas. This remains a viable hypothesis worthy of further study.

D. G. Korycansky & K. J. Zahnle (2003). "High resolution simulations of the impacts of asteroids into the venusian atmosphere III: further 3D models." *Icarus 161,* 244-261.
More detailed numerical modeling of big weak asteroids striking a thick planetary atmosphere.

J. Alvarellos, A. Dobrovolskis, P. Hamill, & K. Zahnle (2002). "Orbital dynamics of Gilgamesh impact ejecta." *Icarus 160,* 108--123.
This is a study of how readily impact ejecta are scattered between the Galilean satellites. We found that about 10% of the ejecta escaping from Ganymede reached Callisto and Europa (each), and 1% reached Io. The rest hit Ganymede.

K. Zahnle, P. Schenk, S. Sobieszczyk, L. Dones, and H. Levison (2003). "Cratering rates in the outer solar system." *Icarus 163*, 263-289.
An update on cratering rates by comets and asteroids throughout the outer soar system. The emphasis as always remains on the age of Europa's sparsely cratered ice shell.

P. Schenk, C. Chapman, and K. Zahnle (2004). "Ages and Interiors: The cratering record of the Galilean satellites. In *Jupiter: The Planet, Satellites and Magnetosphere,* F. Bagenol, T. Dowling, and W. McKinnon, eds. Cambridge Univ. Press. pp. 358-384. (2004).
A review chapter.

J. Harrington, I. de Pater, S. H. Brecht, D. Deming, V. Meadows, K. Zahnle, and P. Nicholson (2004). "Lessons from Shoemaker-Levy 9 about Jupiter and Planetary Impacts." In *Jupiter: The Planet, Satellites and Magnetosphere,* F. Bagenol, T. Dowling, and W. McKinnon, eds. Cambridge Univ. Press. pp. 158-184. (2004).
A review chapter; my part is an update on the chemical consequences of the impacts.

D. G. Korycansky, & K. J. Zahnle (2004). "Atmospheric impacts, fragmentation, and small craters on Venus." *Icarus, 169*, pp. 287-299.
The smallest impact craters on Venus are generally fields of craters made by the debris of the asteroid. We show that, to first approximation, the crater fields are reasonably well described by purely hydrodynamic forces causing stochastic breakup of nonspherical impactors.

J. N. Cuzzi and K. J. Zahnle (2004). "Material enhancement in protoplanetary nebulae by particle drift through evaporation fronts." *Astrophys. J. 614,* 490-496.
Radial transport of meter-sized chunks of rock and ice in the nebula is fast and serves to efficiently separate condensable materials from hydrogen, helium, and neon. When the condensates get close enough to the Sun they evaporate, thus raising their presence in the gas. Turbulence allows condensates to concentrate near the evaporation front.

D. G. Korycansky, & K. J. Zahnle (2005). "Modeling Crater Populations on Venus and Titan." *Planet. Space Sci. 53,* 695-710.
An attempt to predict the impact craters on Titan.

A. Meibom, N. H. Sleep, K. J. Zahnle, and D. L. Anderson (2005). "Models for noble gases in mantle geochemistry: some observations and alternatives." In Foulger, G.R., Natland, J.H., Presnall, D.C., and Anderson, D.L., eds.,

Plates, Plumes, and Paradigms: Geological Society of America Special Paper 388, p. 347–363.

D. Catling, C. R. Glein, C. P. McKay, and K. Zahnle (2005). "Why O2 is required by complex life on habitable planets and the concept of planetary 'oxygenation time.' *Astrobiology 5,* 415-438.
The paper makes two points: (i) the energy in O2 makes large animals possible and (ii) that large animals are not possible until enough hydrogen has escaped to space.

J. Alvarellos, A., Dobrovolskis, P. Hamill, & K. Zahnle (2005). " Fates of satellite ejecta in the Saturn system." *Icarus 178,* 104-123.
In contrast to the Galilean satellites, most of Saturn's satellites are too small to gravitationally scatter impact debris significantly.

K. Zahnle (2005). "Being there" *Nature 433*, 814-815.

K. Zahnle & N. H. Sleep (2006). "Impacts and the early evolution of life." In *Comets and the Origin of Life,* P. Thomas, R. Hicks, C. Chyba, & C. McKay, eds. Springer, Berlin-Heidelberg, pp. 207-252.
This was significantly revised and updated for the second edition of the book.

C.V. Manning, C.P. McKay, & K.J. Zahnle (2006). "Thick and thin models of the evolution of carbon dioxide on Mars." *Icarus 180,* 38-59.

K.J.Zahnle (2006). "Earth's first atmosphere." *Elements 2*, 217-222.
This is a general overview of Earth after the Moon-forming impact, aimed at a nonspecialist audience.

M. Claire, D. Catling & K. Zahnle (2006) "Biogeochemical modeling of the rise of atmospheric oxygen" *Geobiology 4,* 239-269.
This study investigates the hypothesis that hydrogen escape caused the rise of oxygen by oxidizing the continents and thereby changing the redox state of metamorphic gases.

K.J. Zahnle, M. Claire, & D. Catling (2006) "The loss of mass-independent fractionation in sulfur due to a Paleoproterozoic collapse of atmospheric methane" *Geobiology 4,* 271-283.
We use an improved 1D photochemical model to show that mass independent fractionation of sulfur is shut off by reducing the amount of methane in the atmosphere, rather than by increasing the amount of O2 in the atmosphere. Our time-line fits the observed sequence of events better.

K.J. Zahnle, N. Arndt, C. Cockell, A. Halliday, E. Nisbet, F. Selsis, & N. H. Sleep (2006). "Emergence of a Habitable Planet" *Space Science Reviews 129,* 35-78.
This is a more complete draft of Earth's history after the Moon-forming impact.

E.G. Nisbet, K.J. Zahnle, M.V. Gerasimov, J. Helbert, R. Jaumann, B.A. Hofmann, K. Benzerara, and F. Westall (2006) "Creating habitable zones, at all scales, from planets to mud micro-habitats, on Earth and on Mars." *Space Science Reviews 129*, 79-121.

Y. Abe, A. Abe-Ouchi, N. H. Sleep, K.J. Zahnle "Habitable Zone Limits for Dry Planets" submitted to *Astrobiology* [in revision].
Here it is shown using a spartan GCM that a dry (desert) planet is more stable against the runaway greenhouse effect than is a wet (oceanic) planet. It is also shown that the dry planet is more stable against an ice-albedo runaway than is a wet planet. Thus a dry planet has a wider habitable zone than a wet planet.

P.M. Schenk and K.J. Zahnle (2007) "On the negligible surface age of Triton." *Icarus 192*, 135–149.
Triton, captured comet now moon of Neptune, has a younger surface than Europa.

D. C. Catling, M. W. Claire, and K. J. Zahnle (2007) "Anaerobic methanotrophy and the rise of oxygen," *Phil. Trans. Roy. Soc. A, 365*, 1867-1888.
Investigates the competition between sulfate eaters and methane makers.

K.J. Zahnle, N. Arndt, C. Cockell, A. Halliday, E. Nisbet, F. Selsis, & N. H. Sleep (2007). "Emergence of a Habitable Planet" In *Geology and Habitability of Terrestrial Planets*, K.E. Fishbaugh, P.L. Lognonné, F. Raulin, D.J. Des Marais, O. Korablev (Eds), Springer, pp. 35-78.
This is a more complete draft of Earth's history after the Moon-forming impact. It treats Earth's Hadean as an Eon to interpolate between initial conditions set by the moon-forming impact and the emergence of recognizable rocks on the face of the Earth some 600 million years later.

E.G. Nisbet, K.J. Zahnle, M.V. Gerasimov, J. Helbert, R. Jaumann, B.A. Hofmann, K. Benzerara, and F. Westall (2007) "Creating habitable zones, at all scales, from planets to mud micro-habitats, on Earth and on Mars." In *Geology and Habitability of Terrestrial Planets,* K.E. Fishbaugh, P.L. Lognonné, F. Raulin, D.J. Des Marais, O. Korablev (Eds), Springer, pp. 79-121.

J. Alvarellos, A., Dobrovolskis, P. Hamill, & K. Zahnle (2007). "Transfer of mass from Io to Europa and beyond due to cometary impacts" *Icarus 194*, 636-646.
This study addresses the transport of impact ejecta from craters on Io to Europa.

K.J. Zahnle, J. Alvarellos, A., Dobrovolskis, & P. Hamill (2007). "Secondary and Sesquinary Impact Craters on Europa" *Icarus 194*, 660-674.
This study addresses what happens when impact ejecta from Io strike Europa. We develop a general description of conventional secondary cratering and sesquinary cratering (meaning craters on satellites made by impact ejecta that achieve orbit about the planet). It makes predictions for the amount of Ionian basalt that should be present on Europa.

C.V. Manning, C.P. McKay, & K.J. Zahnle (2008). "The nitrogen cycle on Mars: Impact decomposition of near-surface nitrates as a source for a nitrogen steady state." Accepted by *Icarus (in press)*.
This study suggests that nitrogen in the atmosphere of Mars is in steady state between escape and a source in impact decomposition of surface nitrate minerals.

E.B. Bierhaus, K.J. Zahnle, C.R. Chapman (2008). "Europa's Crater Distributions and Surface Ages." In *Europa: The Great White Hope.* R. Pappalardo and W.B. McKinnon, Eds. Lunar and Planetary Institute (submitted).
We confront our theory of secondary and sesquinary cratering of Europa with the best available actual crater counts on Europa. There is more work to be done.

K.J. Zahnle, R.M. Haberle, D.C. Catling, J.F. Kasting (2008). "The Photochemical Instability of the Ancient Martian Atmosphere." Submitted to *J. Geophys Res.*
We construct a new 1D model of martian atmospheric photochemistry, tune it to modern Mars, and then apply it to ancient Mars. Our new model provides a better fit to the observed abundances of CO, O2, and H2 than previous published models. When applied to ancient Mars, the photochemical model predicts that a CO2 atmosphere would have been unstable with respect to CO.